Electron cooling for the Recycler ring
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Sergei Nagaitsev

Background
A charged particle (i.e. an antiproton) traveling in an electron beam undergoes Coulomb scattering with the electrons. The resulting friction and velocity diffusion tends to bring such particles into thermal equilibrium with the electrons. If the particle kinetic energy in the beam frame is high in comparison with the electron temperature, diffusion is insignificant and the particles are cooled – this is, in essence, a simplified description of the electron cooling method. This method was originally suggested by A. M. Budker [1]. It was developed and studied both theoretically and experimentally; an ample list of references can be found in Ref. [2], for example.

Fermilab started in 1995 to investigate the application of electron cooling to 8.9 GeV/c antiprotons in the Recycler as a promising component of an upgrade of Tevatron luminosity beyond the Run IIa goals. The idea was not entirely new at that time; it had been proposed as an upgrade path for the Accumulator as early as 1985 [3], and there had been some experimental work as well as conceptual development [4]. The practice and principles are well established for protons/ions with kinetic energy of less than 500 MeV/nucleon. For ions of higher energy the fundamentals are the same, but hardware development is required and the technical problems differ. Technical details about the Fermilab R&D program can be found in Ref. [5]. To date, electron cooling at relativistic energies remains an unproven technology, and thus constitutes a high-risk segment of the RunII upgrades plan. Fermilab is currently the only laboratory pursuing the high-energy electron cooling R&D at full scale; conceptual and experimental studies for similar systems are being carried on at Budker INP (Russia), BNL (USA), DESY (Germany), and GSI (Germany).

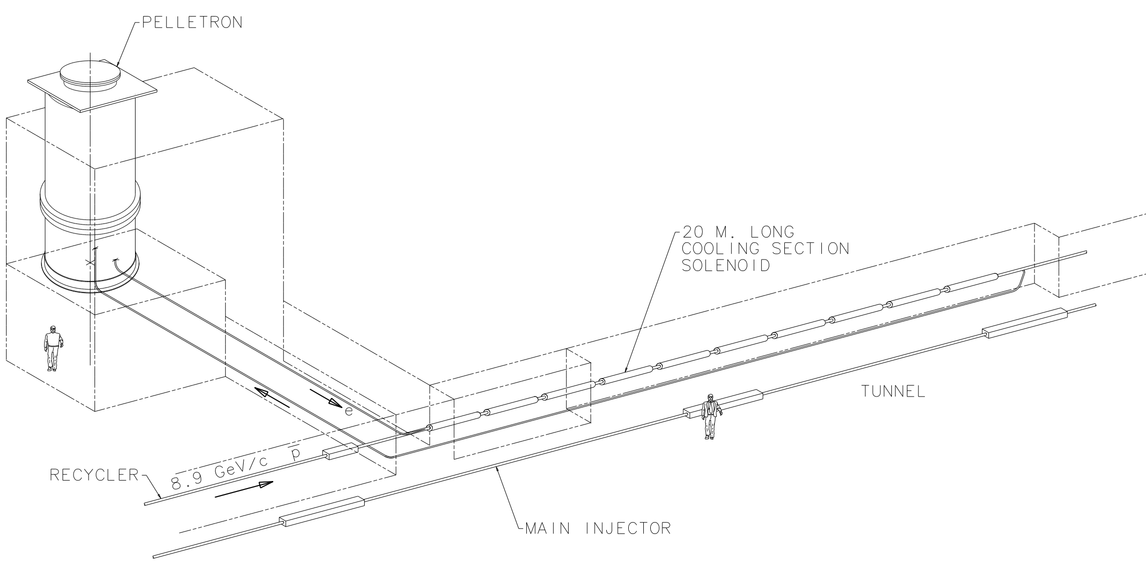

Figure 1: Schematic layout of the Recycler electron cooling system.

The Recycler currently employs a stochastic cooling system to collect multiple batches from the Accumulator. Electron cooling will improve cooling performance in the Recycler, permitting to have faster stacking and larger stacks. In combination with other accelerator upgrades it will permit substantially greater luminosity in the collider. The Recycler electron cooler, discussed here, will be installed in the MI-30 section of the Recycler tunnel and it is schematically shown in Figure 1.

Motivation
Electron cooling can reduce the spread in all three components of beam momentum simultaneously. Its primary advantage over stochastic cooling is that the cooling effect is practically independent of antiproton beam intensity up to the Recycler stack sizes of about 2×10^{13} antiprotons. Its greatest disadvantage is that the effect is very weak until the antiproton transverse emittances are already close to the values wanted in the collider. Thus, the two processes can be seen as complementary rather than competitive. Electron cooling will prove very powerful in the Recycler as an add-on to the stochastic pre-cooling in the Antiproton Source and Recycler.

Purposes of a Recycler beam cooling system (stochastic or electron) are:
1. To aid beam staking in the Recycler during frequent transfers from the Accumulator;
2. To counteract various beam heating mechanisms, such as residual-gas and intra-beam scattering.

For Run2a, the transverse stochastic cooling system alone is thought to be adequate; the attainable emittance cooling rate is thought to be about 15 π mm-mrad/hour (normalized, 95%) for modest stack sizes. Electron cooling and stochastic cooling are complementary, in principle, and, at least, during the earliest operation of the electron cooling system, that complementarity will be exploited by using the stochastic cooling for the large transverse emittance of the antiprotons whereas the electron cooling will be optimized for longitudinal cooling to increase the stacking rate and maximum stack current. At the time of writing this report the Recycler stochastic cooling system has not been fully commissioned.

The ultimate goal is to realize a peak luminosity of 3×10^{32} $cm^{-2}s^{-1}$ in the Tevatron collider by supplying a larger flux of antiprotons. Our conceptual design studies demonstrate that this can be accomplished by providing longitudinal emittance cooling rates in the Recycler of 80 eV·s/h or higher (in conjunction with the transverse stochastic cooling). The specific technical goal for the Recycler with the electron cooling system is to deliver 6×10^{12} antiprotons with a 50 eVs (or less) longitudinal phase-space area (98%) and 10 μm transverse emittance (95%, norm.) in 8 hours.

System parameters
The electron cooling system parameters are primarily determined by the technical goal for longitudinal cooling rates of 80 eV·s/h or higher, and by the electron and antiproton beam matching requirements. At present, all technical parameters for the electron cooling system are optimized for longitudinal cooling only.

The following parameters affect the longitudinal cooling rates:

- It is proportional to the cooling section length. Once the length is set, the optimal value of the antiproton beta-function and the electron beam radius are determined.
- It is proportional to the electron beam current.
- It falls down sharply if the effective electron angular spread in the cooling section is greater than the antiproton rms angular spread $\theta_p \approx 0.1$ mrad. The specific dependence is greatly affected by the nature of this spread: temperature, misalignment, aberration etc.

Figure 2 shows the calculated evolution of a longitudinal antiproton momentum distribution function.

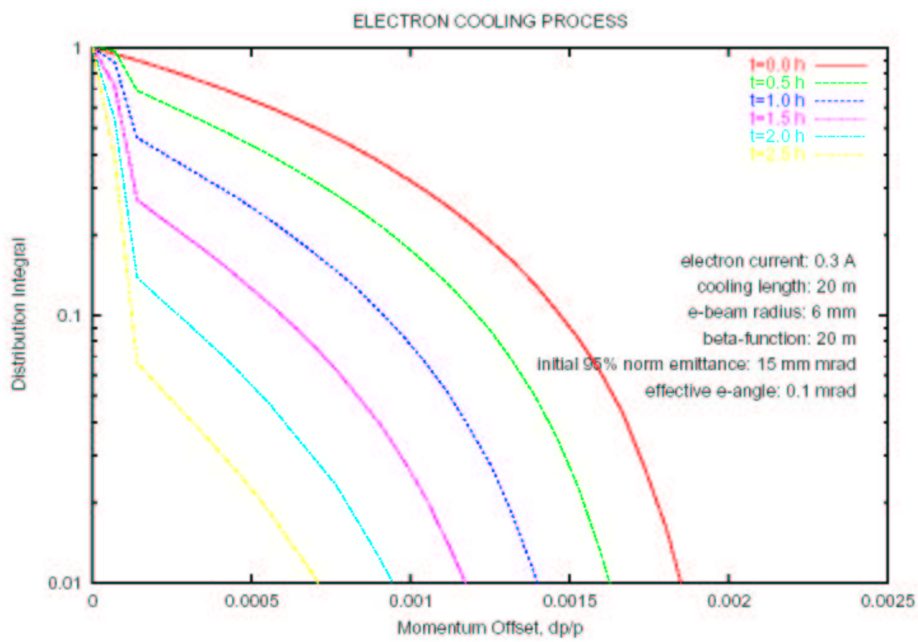

Figure 2: The calculated evolution of the longitudinal momentum spread. The initial distribution is parabolic in momentum; a coasting antiproton beam is assumed to have the total longitudinal emittance of 400 eV-s. The vertical axis represents the fraction of particles outside of the +/- interval for a given momentum on the horizontal axis.

From Fig. 2 one can see that the predicted momentum cooling rate, $\frac{d}{dt}\frac{dp}{p}$, for a particle at the edge of the distribution ($dp/p \approx 0.002$) is $5 \cdot 10^{-4}$ hr^{-1}. If such a beam fills the entire Recycler circumference this would correspond to a 25 eV-s/hour longitudinal phase-space area cooling rate. Thus, the required dc electron beam current to meet the 80 eV-s/hour goal is 400 mA or greater.

Table 1 presents important parameters of the Recycler electron cooling system.

Table 1: Electron Cooling System Parameters

Parameter	Design value	Achieved or installed	Units
Electrostatic Accelerator			
Terminal Voltage	4.34	4.34/3.5	MV
Electron Beam Current	0.5	0.5/1.0	A
Terminal Voltage Ripple	500	500	V (FWHM)
Cathode Radius	2.5	2.5	mm
Gun Solenoid Field	≤ 600	600	G
Cooling Section			
Length	20	18	m
Solenoid Field	≤ 150	150	G
Vacuum Pressure	0.1	wip (work in progress)	nTorr
Electron Beam Radius	6	wip	mm
Electron Beam Divergence	≤ 80	wip	μrad

These parameters identify a system, which is unlike any other electron cooling system in the world. It requires a 4.36 MV power supply operating with a 2-MW beam in a high-efficiency recirculation regime. Our choice of a commercial 4.36-MV Van-de-Graaff type supply forced us to undertake an R&D of two new technologies in (1) beam transport and (2) magnet technology.

1. Early in the design stage we determined that the best way to focus the electron beam in the 20-m long cooling section is to use a weak 150-G solenoid. Such a solenoid becomes effective only if the electron beam enters it with a matched angular momentum to cancel the solenoid edge effects. The only way to impart an angular momentum onto the electron beam is to immerse the electron gun in a solenoidal magnetic field. Naturally, such a solenoid can only be of limited length because of high-voltage restrictions in the Peletron terminal. Thus, we designed a beam transport line in which a beam is produced by a 5-mm diameter cathode in a 600-G magnetic field and then propagated to the cooling section, where it is injected into a 150-G solenoid. The beam exits the gun solenoid at a fairly low energy (about 500 keV) and rapidly expands due to its angular momentum. While the defocusing effect of the angular momentum is reduced by further beam acceleration, nevertheless, it remains to be a driving term in the envelope equation – by far greater than both the emittance and space-charge terms. We called this beam transport regime an angular-momentum dominated regime [6]. This regime will be fully tested during the second stage of the R&D program.

2. The cooling section solenoid is unlike the solenoids that are presently used in all of the low-energy electron coolers. Because of its low magnetic field (about 100 G) and high electron beam energy, the field quality requirement is set on the transverse field integral rather than on the value of the transverse field itself. Thus, short-range (30 cm or less) field fluctuations become less important than the long-range alignment. Details of our solenoid design can be found in Ref. [7].

Research and development goals

It was determined that the most effective way to attain these parameters was to conduct the development in two stages by: (1) demonstrating the beam current, voltage and necessary stability in a short 10-m long beamline and (2) commissioning the full-scale 60-m long beam line prototype. To achieve the required system parameters Fermilab has created an electron cooling R&D facility at the WideBand Lab building. This R&D program was registered as an approved Fermilab experiment E-901. A 5-MV Van de Graaff accelerator (Pelletron) has been purchased and installed at WideBand. This accelerator together with an electron beamline forms an R&D facility. A prototype beamline closely resembles the final beamline. Most of its elements will be reused in the MI/RR tunnel. In addition, all of the Pelletron equipment will be reused. The purpose of this R&D program is to develop a system ready to install in the Recycler tunnel. The program, however, will come short of actual antiproton beam cooling – this will be commissioned in the Recycler ring.

At present, the R&D program is in transition between the first and second stages. The successful completion of the first stage of the program allowed us to proceed with the civil construction of a building near the Recycler tunnel, where the electron cooler will be housed. The new building is scheduled to be completed in March, 2004, at which time the electron cooling equipment will be moved to its final location. The cooling section installation in the Recycler tunnel is scheduled for the summer of 2004.

Status

The beam recirculation test

The recirculation experiment at Fermilab was performed in 2001 – 2002 with a system, which included an electrostatic accelerator, Pelletron, and a short beam line (U-bend). After attainment of a 0.5-A, DC electron beam at the kinetic energy of 3.5 MeV in December, 2001 [8], the main efforts on the final stage of the experiment, in May-November, 2002 were devoted to improving of the beam operational stability.

Estimations made for the future electron cooler has shown that infrequent short-duration processes in the Pelletron, like beam interruptions or discharges, would not deteriorate the performance of the Recycler ring. A weak interaction (i.e. cooling) between the electron and antiproton beams makes heating of the antiproton beam during electron current interruptions negligible; a long beam line between the Pelletron and the common cooling section preserves the high vacuum in the Recycler ring in cases of pressure bursts in the accelerating tubes. Therefore, the figure of merit for electron beam stability is an average duty factor of the electron beam operation.

Several processes affected the duty factor in the recirculation experiment. First, a stable recirculation of a DC beam can be interrupted by sudden jumps in current losses, which forces the protection system to shut the electron gun off. Second, full acceleration tube discharges can result in large changes of the residual gas pressure and tube's high voltage stability. Third, the full discharges sometimes result in a cold emission from the gun control electrode, which has to be conditioned away before restoring the beam

recirculation. These issues are described in detail in Ref. [9]. The cold gun emission was nearly completely eliminated by a proper choice of the gun electrode materials.
As for the beam interruptions and tube discharges, the system behaved differently at a Pelletron voltage of 3.5 MV and 4.34 MV. We found that while without any beam the accelerating gradient can be as high as 16 kV/cm (corresponding to 5 MV), with the dc electron beam in excess of 10 mA the stable operating gradient drops to 12 kV/cm. This prompted us to plan an upgrade for the Pelletron from 5 to 6-MV maximum rating by extending the acceleration tube length by 20%. This upgrade will be implemented when the Pelletron is moved to its final location. With this upgrade the accelerating gradient at the design voltage of 4.34 MV will be very close to that of the present machine at 3.5 MV. Table 1 shows the achieved results for two voltages – 4.34 and 3.5 MV. While at 4.34 MV we were able to demonstrate the design current of 0.5 A, the stable beam operation was frequently interrupted by beam-induced tube discharges (every 4 minutes or so) with eventual high-voltage de-conditioning such that the Pelletron was no longer capable of holding 4.34 MV. At a lower 3.5-MV voltage and best beam line settings we did not see any full-tube discharges, while the beam interruptions occurred on average every 20 minutes (with a 0.5-A beam) and did not cause any de-conditioning to the accelerating tube. Figure 3 shows a 4-hour run with a 0.5 A beam at 3.5 MV.

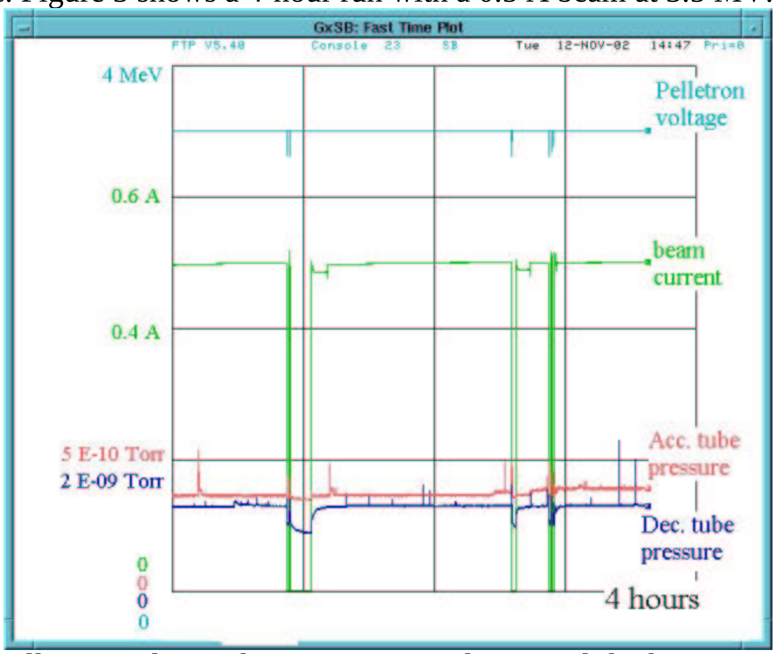

Figure 3: The Pelletron voltage, the ion gauge readings, and the beam current recorded over 4 hours of running at 3.5 MV, 0.5 A. An interruption in the first hour was caused by a computer glitch.

In all beam interruptions the Pelletron voltage drops by no more than 200 kV. This prompts the computer control system to shut the electron gun off. The Pelletron voltage then returns to its nominal value in several seconds; the recirculation at the nominal current is restored in 20 seconds by the control system without any operator interference. Figure 4 shows the beam recovery process on a shorter time scale.

Putting aside mechanical and electronics failures, at 3.5 MeV, 0.5 A, and the best conditions, only the short beam interruptions were present, and the duty factor was better than 99%, which is sufficient for cooling. While the current of 0.5 A has been achieved at the energy of 4.34 MeV, multiple interruptions led to full discharges and loss of tube conditioning. The necessity to recondition the tubes makes such a regime intolerable. The level of the beam current at 4.34 MeV, at which the duty factor is above 95%, is 0.1 A or less.

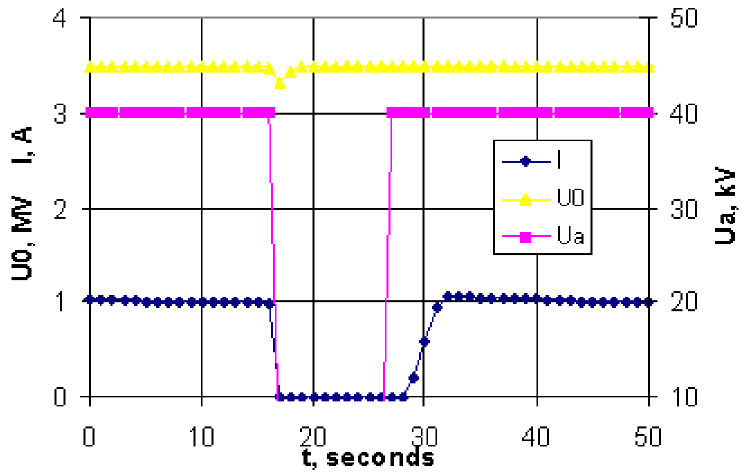

Figure 4: Beam recovery after an interruption of a 1-A beam recirculation. The electron gun was operated with a 40-kV anode voltage (Ua curve).

We are implementing several improvements to enable a stable operation at the nominal energy (4.36 MV) in the final setup. The major one is an addition of a 1-MV section to the Pelletron to decrease the tube electric field by 20%. Other changes are designed to decrease the irradiation of the deceleration tube during the recirculation interruptions by:

- making the value of the dispersion function in the deceleration tube as low as possible and intercepting the beam with a lowered energy inside bends;
- applying a crowbar between the cathode and the gun anode after detecting an interruption on a microsecond-scale time.

With these modifications, we expect the performance at nominal parameters will be similar to that at 3.5 MeV at present.

The full-scale beam line

All elements of a long beam line prototype are currently being installed. A 90-degree achromatic bend has been measured with a proton beam and has shown a good field quality. Operations with a beam in the full-scale beam line will start in June of 2003.

Cooling section solenoid

The 20-m cooling section solenoid in the Recycler tunnel will consist of ten solenoid modules, gaps between the modules and magnetic field correctors [10]. The transverse field in the cooling section is measured by a dedicated compass-based magnetic sensor, while the longitudinal field is measured by a Hall probe.

For the successful cooling it is necessary to keep electron angles below 0.1 mrad inside the cooling section (see Table 1). This requirement in turn sets several restrictions on the magnetic field quality: the longitudinal field at any point in the cooling section shouldn't differ too much from the field averaged over the whole cooling section and the absolute value of a running integral of the transverse field should be kept below 1G·cm at any point inside the cooling section [10].

The measured transverse field of an uncorrected solenoid does not satisfy these requirements. Indeed, the simulation of the electron motion in this un-corrected field showed that the acquired angles are as large as 5 mrad.

To improve the field quality, an algorithm of field compensation was suggested [11]. Initially, it was tested in a 4-meter prototype of the cooling section. It was found that the algorithm works reliably and gives the field of the proper quality.

Following that, the cooling section solenoid consisting of 9 identical 2-m long modules has been installed in a mock-up tunnel. The uncorrected field of this 18-m long cooling section was measured and used as an input for the algorithm. The calculated currents of the transverse correctors were used to predict the compensated field. Figure 5 shows the total electron angle in this expected field, with 95% of the cooling section being better than the design goal of 0.1 mrad.

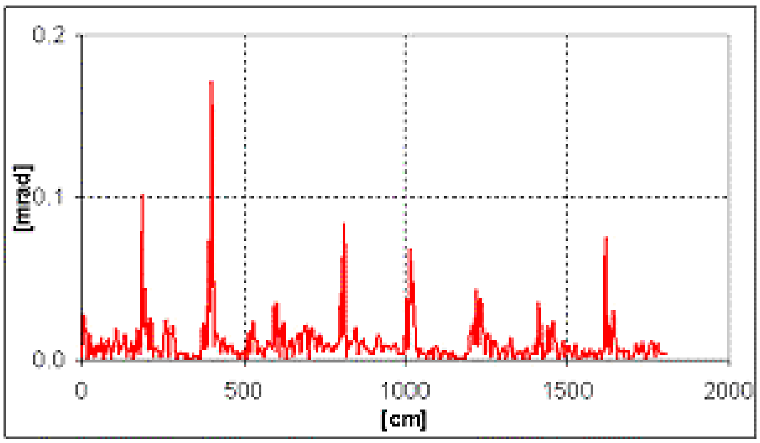

Figure 5: The simulation of the total electron angle along the cooling section, calculated under the assumption that the transverse field components are compensated by dipole correctors in an optimum way (an electron enters the solenoid at 5mm off axis).

After the compensated field had been measured, the analysis showed its unsatisfactory quality; although the compensated field is somewhat 10 times better than the initial one (see Figure 6) it is still a factor of 3-4 worse than the design goal.

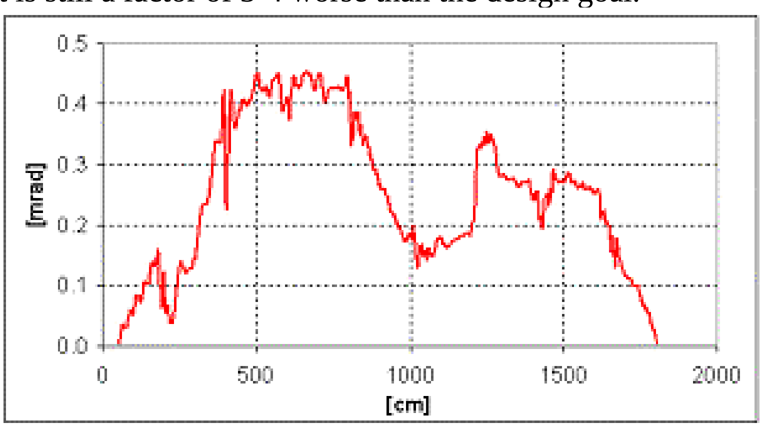

Figure 6: The total electron angle simulated in the fields, obtained after the adjustments of field correctors (an electron enters the solenoid at 5mm off axis).

At present, we believe that the reasons for the discrepancy between the expected electron angles (Fig. 5) and Fig. 6 are [12]:

1. the unsatisfactory long-term reproducibility of the sensor (largest contribution);
2. the imprecise calibration of the transverse field correctors;
3. the rotation of the cart that transports the compass sensor.

Summary:
The solenoid quality is, in principle, good enough to provide electron angles below 0.1 mrad on 95 % of the cooling section length, provided all dipole correctors are set to optimum. After the long-term stability of the sensor is improved, mostly by improving the reference laser beam pointing stability, the fields in the cooling solenoid will be re-measured in July-Aug, 2003. We believe that with work we will achieve the design field quality.

Civil construction

The civil construction for the electron cooling system (building MI-31) has begun on April 14, 2003. The expected construction complete date is March 12, 2004. Monthly updates on the construction progress can be found in Ref. [13].

Project plan
Although electron cooling is well understood, the Recycler application represents a major step in beam energy, to 8 GeV from less about 0.5 GeV. The step is large enough that the high voltage generator, beam transport, and cooling region all require extension of the state of the art. Therefore, about 1 year (as of March, 2003) of research and development activity are likely to precede introduction of any electron cooling equipment into the Recycler.

The R & D phase of the project has the following plan:

1. To develop an optimized system parameter set (finished);

2. To procure and commission a reliable 4.3 MV electrostatic power supply (finished);

3. To design and build an electron beam gun, collector and short (10 m) U-bend transport system to sustain a recirculating current of at least 0.5 A for 1 hour (finished);

4. To design and implement a precise matching from discrete-element beam transport to continuous cooling region solenoid;

5. To design and implement a 20 m cooling section with uniform axial magnetic field with precision such that electron beam transverse angles are $\leq 10^{-4}$;

6. To design and implement magnetic shielding to protect the electron beam against the magnetic fields of the MI/RR tunnel;

7. To design and build beam instrumentation and controls to maintain alignment and equal mean velocity of electron and p-bar beams to precision $\leq 10^{-4}$, to measure beam angular spread and position, to determine neutralization, *etc*.;

8. To assemble a full-scale (60 m) beam line, commission it and establish a recirculating beam current of at least 500 mA at 4.3 MeV, sustainable for 24 hours with a duty cycle of no less than 90%;

9. To demonstrate by measurements that the electron beam angles in the cooling section are $\leq 10^{-4}$.

The hardware aspects of the development program are treated in detail in Ref. [5]. The remainder of the work constitutes an Accelerator Improvement Project of moderate scale.

The basic tasks are:
1. Architectural design and civil construction of an enclosure for the high voltage generator and an interconnection tunnel to the MI tunnel for the electron beam transport (complete);

2. Installation of a Recycler lattice insertion for the cooling region. This task is almost finished. The Recycler lattice suitable for the electron cooling system exists. However, some p-bar trim magnets, diagnostics, and vacuum equipment will have to be installed upstream and downstream of the cooling section at the time of the cooler installation;

3. Installation of cooling section and electron beam transport channels;

4. Commissioning of the cooling system.

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